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## 11<sup>th</sup> International Conference on Urban Drainage Modelling

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### Using the Ensemble Kalman Filter to update a fast surrogate model for flow forecasting

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**Abstract:** Many cities face issues with rain induced flooding and combined sewer overflows, which can be addressed by using hydrodynamic models. These models are often simplified in a real-time setting to make them faster, and their performance can be improved by using data assimilation. In this study we use the Ensemble Kalman Filter to update a simplified model of a small area of Copenhagen, Denmark. The model is evaluated using perfect rain data for one summer month in 2016, and flow forecasts are used to quantify the performance of the update. We found that the 1-60 minutes forecast can be improved by updating the model. Having a small noise on the rain gives slightly worse results on a short forecast horizon and slightly better forecasts on a longer horizon. The forecast performance is also dependent on which model parts are updated.

**Keywords:** Data assimilation; surrogate model; flow forecasting

## 1. INTRODUCTION

Changes in precipitation patterns and increased urbanisation will often lead to increased runoff. This increase may result in more frequent bypasses at the wastewater treatment plants, flooding of streets and discharge of polluted mixed storm- and wastewater through combined sewer overflows (CSOs). Real-time urban drainage models, spanning from simplified models to detailed 1D hydrodynamic models (high-fidelity (HiFi) models), can be used to monitor the system and localize misbehaviours, forecast flooding or make a more optimal control of the system to reduce negative effects of the increased runoff. The reduction in computational cost is the main incentive to use simplified models. The uncertainty can be reduced by using measurements from the sewer system to update the real-time model every few minutes (also known as *data assimilation*). Data assimilation is well-known in many fields, but has not been used often within urban drainage (see Borup et al. 2011, 2014, 2015; Branisavljevic et al. 2014, Hansen et al. 2011; Hutton et al. 2014).

Model predictive control (MPC) of sewer systems typically employs a combination of various models (Lund et al., 2018), including models that produce flow inputs for the MPC. The fast and simple surrogate model by Borup et al. (2017) is developed for this purpose, and has the advantages of being thousands of times faster than the HiFi models they are constructed from, while maintaining the ability to predict key outputs. They furthermore do not have to rely on historical data for parameterization. The objective of this study is to quantify to which extent data assimilation can improve the forecast quality of these models by using downstream flow measurements. The update is done every minute using the Ensemble Kalman Filter (EnKF) since this works well with non-linear models and provides useful initial conditions for ensemble based forecasts, which is the long term goal of the proposed setup.



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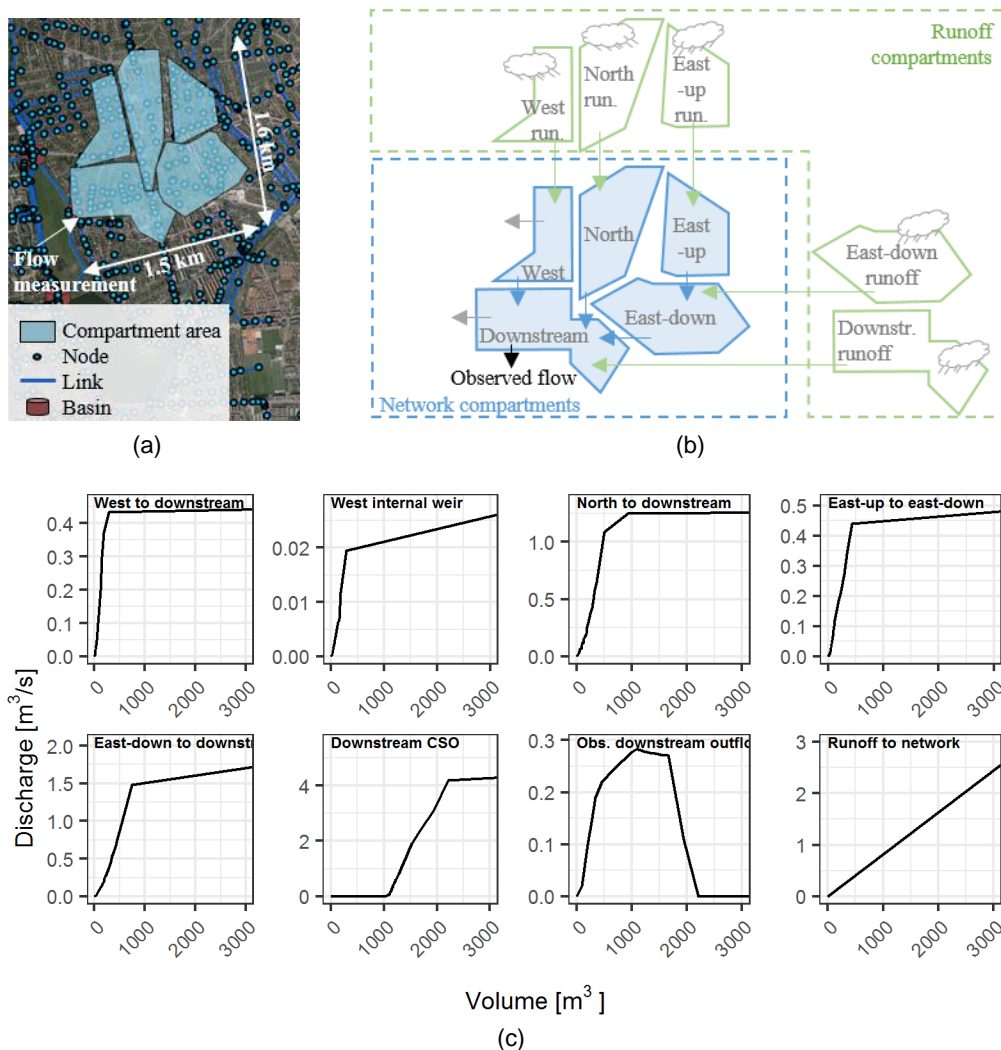
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To our knowledge, the use of the EnKF to update fast surrogate models has not previously been studied within urban drainage.

## 2. MATERIALS AND METHODS

### 2.1 Surrogate model and data

We use a catchment of approximately 1.5x1.6 km<sup>2</sup> in Copenhagen, Denmark, as case study. The area is modelled using a surrogate model consisting of *compartments*, which each consists of one or more piecewise linear volume-discharge curves. These have been calibrated from a MIKE URBAN model (see Borup et al. (2017)). Figure 1 shows the setup of the compartment model. This area is of particular interest because it previously has been used in a MPC study (Lund et al. (2017)).



**Figure 1.** (a) MIKE URBAN model and its division into compartments; (b) Conceptualization of compartment model; (c) Volume-discharge curves for the network and the common curve for all runoff compartments.

The model is forced with one-minute rainfall data from June 16 to July 13, 2016. The rain measurements are obtained from the rain gauge SVK 5710 placed 0.5-2 km outside of the considered area. The surrogate model was constructed using synthetic rain data; thus, the



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model itself does not compensate for any errors in the observed rainfall. The rain is translated to flow in the five runoff compartments simply by multiplying the rain intensity with the impermeable surface area of each compartment while a dry weather flow component is added to the downstream compartment. The runoff and network compartments mimic the runoff and network simulation of MIKE URBAN, respectively. Flow measurements are obtained from the outlet of a CSO structure located in the downstream end of the catchment for the same time period.

### 2.2 The Ensemble Kalman Filter

EnKF is a Monte Carlo implementation of the standard Kalman Filter in which an ensemble of models is used to represent the model uncertainty. Each model in the ensemble is represented by its state vector, which in the current example is a vector with all compartment volumes. The essence of the EnKF is that the ensemble is used to calculate the Kalman gain which then is used to adjust the values of the state vectors in the ensemble itself when new observations are available. In this way the information present in the observations is sequentially integrated into the ensemble and the ensemble mean is assumed to be the best estimate of the truth (more information can be found in Evensen (2003)).

In this study, we apply an ensemble size of 50 ensemble members. The relative error in the rainfall data is assumed uniformly distributed (Eq. 1) while the relative error in the observations is assumed normally distributed (Eq. 2)

$$I_{ens}(t) = I_{obs}(t)\epsilon_{rain,perturb}(t), \epsilon_{rain,perturb}(t) \sim U[lim_{min}, lim_{max}] \quad (1)$$

$$Q_{ens}(t) = Q_{obs}(t)\epsilon_{obs,perturb}(t), \epsilon_{obs,perturb}(t) \sim N(1, \alpha Q_{obs}) \quad (2)$$

### 2.3 Flow forecasts and performance evaluation

Flow forecasts from the downstream compartment are compared to the flow measurements to examine the potential of using data assimilation in a forecast setting, for example, as input to MPC. Since we do not know the “truth” for the internal model states, the flow forecasts will also give an indication of the quality of the update of the internal states. In this study we assume “perfect rainfall forecast”, i.e. the forecasted rainfall equals the measured rainfall in the forecast step. We apply deterministic forecasting, i.e. the mean of the ensemble is used as initial conditions in a surrogate model that is run up to 180 min into the future. The Nash-Sutcliffe Efficiency (NSE) is used to evaluate the performance impact of different settings of data assimilation against the baseline scenario without data assimilation. The changes in settings include altering the assumed noise in the rainfall ( $lim_{min}$  and  $lim_{max}$ ) and varying the set of compartments to be updated.

## 3. RESULTS AND DISCUSSION

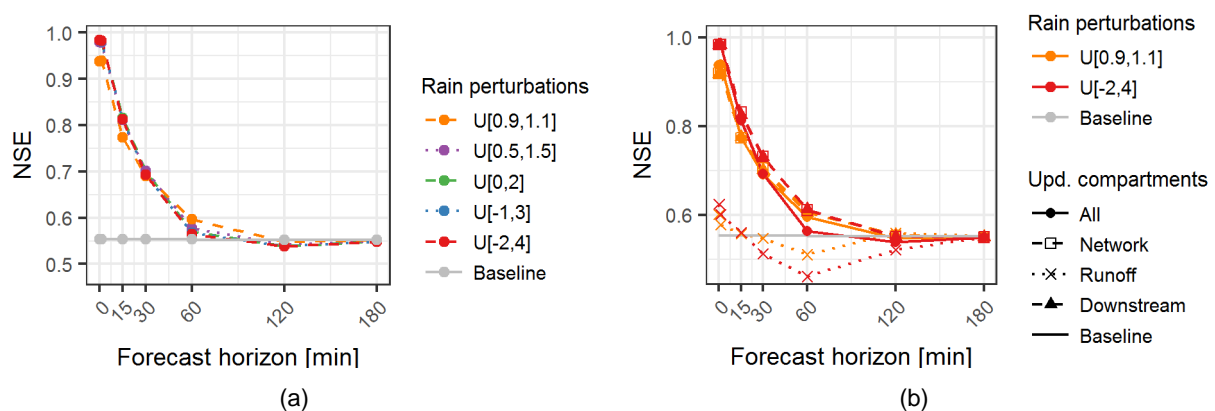
When setting  $\alpha=0.1$  for the noise in observations (Eq. 2) and updating all compartments, we first see that updating the model improves the forecasts 1-60 minutes ahead significantly. We also find that there is no significant difference between having a rain perturbation of  $U[0.5,1.5]$  and  $U[-2,4]$  (negative rain will practically remove water from the runoff compartments). Compared to these settings, the rain perturbation of  $U[0.9,1.1]$  leads to slightly worse performance for shorter forecast horizons and slightly better for longer horizons.



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If we additionally change the set of compartments to update, we see that updating only the runoff compartments performs poorly. When using noise of  $U[0.9, 1.1]$  in the rain, there is no big difference between updating all compartments, network compartments or only the downstream network compartment. Updating the downstream network compartment thus outweighs the update of the other compartments. For a rain perturbation of  $U[-2, 4]$ , forecasts horizons above 15 minutes benefit from not updating the runoff compartments, but is otherwise also dominated by the update of the downstream compartment. Future research will focus on incorporating time correlated noise in rainfall and compare the surrogate model forecast performance with the performance of the corresponding MIKE URBAN model.



**Figure 2.** Nash-Sutcliffe Efficiency of flow forecasts by (a) varying the noise perturbations on the rain, and (b) varying which surrogate model compartments are updated.

## CONCLUSIONS

We use the Ensemble Kalman Filter to update the volumes in a surrogate model of a 2.4 km<sup>2</sup> catchment in Copenhagen, Denmark. We found that updating the model leads to improved 1-60 minutes forecasts. A small rain perturbation decreases the performance for short forecast horizons compared to a larger rain perturbation, and increases the performance for longer forecast horizons. We also found that the performance can be improved by not updating the runoff compartments, but that updating the downstream network compartment generally improved the performance. The immediate future research efforts will focus on including the time correlation of the noise in rainfall in the updating scheme and comparison of the performance with a MIKE URBAN model.

## References

- Borup, M., Grum, M., and Mikkelsen, P.S. (2011). Real time adjustment of slow changing flow components in distributed urban runoff models. *Proceedings of the 12<sup>th</sup> International conference on urban drainage, Porto Alegre, Brazil*.
- Borup, M., Grum, M., Madsen, H., and Mikkelsen, P.S. (2014). Updating distributed hydrodynamic urban drainage models. *Proceedings of the 13<sup>th</sup> International conference on urban drainage, Sarawak, Malaysia*.
- Borup, M., Grum, M., Madsen, H., and Mikkelsen, P.S. (2015). A partial ensemble Kalman filtering approach to enable use of range limited observations. *Stoch. Environ. Res. Risk Assess.* **29**, 119–129.
- Borup, M., Thrysoe, C., Arbjerg-Nielsen, K., Righetti, F., Mikkelsen, P.S. (2017). A fast surrogate model tailor-made for real time control. *Proceedings of the 14<sup>th</sup> International conference on urban drainage, Prague, Czech Republic*, 2486-2488.
- Branisavljevic, N., Hutton, C., Kapelan, Z., Vamvakieridou-Lyroudia, L., and Savić, D.A. (2014). Real-Time Runoff Prediction Based on Data Assimilation And Model Bias Reduction. *11<sup>th</sup> Int. Conf. Hydroinformatics, New York City, USA*.



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- Evensen, G. (2003). The Ensemble Kalman Filter: theoretical formulation and practical implementation. *Ocean Dynamics* **53**, 343-367.
- Hansen, L.S., Borup, M., Møller, A., and Mikkelsen, P.S. (2011). Flow Forecasting in Urban Drainage Systems using Deterministic Updating of Water Levels in Distributed Hydraulic Models. *Proceedings of the 12<sup>th</sup> International conference on urban drainage, Porto Alegre, Brazil*.
- Hutton, C.J., Kapelan, Z., Vamvakieridou-Lyroudia, L., and Savić, D. (2014). Real-time data assimilation in urban rainfall-runoff models. *Procedia Eng.*, 70, 843–852.
- Lund, N., Borup, M., Halvgaard, R., Falk, A. K., Mark, O., Madsen, H., and Mikkelsen, P.S. (2017). Advancing from underground to aboveground model predictive control in urban drainage. *Proceedings of the 14<sup>th</sup> IWA/IAHR International conference on urban drainage, Prague, Czech Republic*, 2486-2488.
- Lund, N.S.V., Falk, A.K.V., Borup, M., Madsen, H., and Mikkelsen, P.S. (2018). Model predictive control of urban drainage systems: a review and perspective towards smart real-time water management. *Critical Reviews in Environmental Science and Technology*, 48(3), 279-339. DOI: 10.1080/10643389.2018.1455484